

## Composite Fuselage Crown Panel Manufacturing Technology<sup>1</sup>

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### ABSTRACT

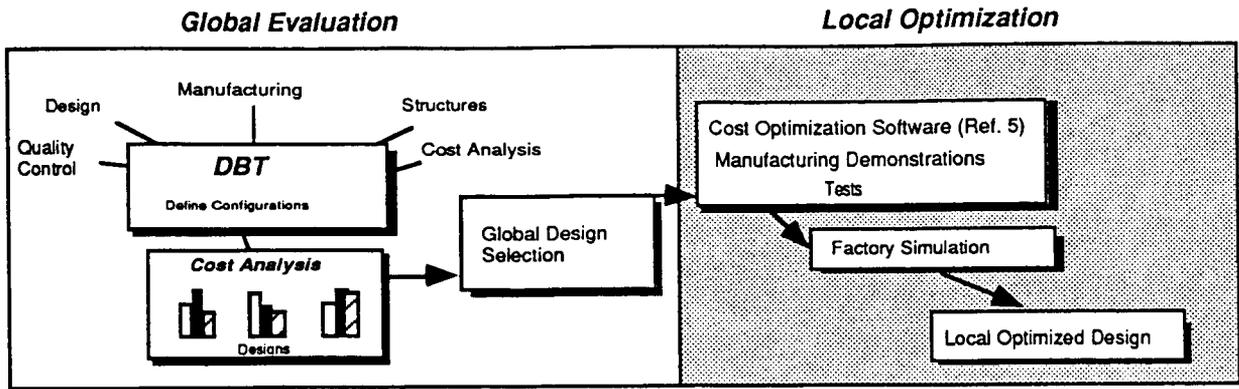
Commercial fuselage structure contains significant challenges in attempting to save manufacturing costs with advanced composite technology. Assembly issues, material costs, and fabrication of elements with complex geometry are each expected to drive the cost of composite fuselage structure. Boeing's efforts under the NASA ACT program have pursued key technologies for low-cost, large crown panel fabrication. An intricate bond panel design and manufacturing concepts were selected based on the efforts of the Design Build Team (DBT) (Ref.1). The manufacturing processes selected for the intricate bond design include multiple large panel fabrication with Advanced Tow Placement (ATP) process, innovative cure tooling concepts, resin transfer molding of long fuselage frames, and utilization of low-cost material forms. The process optimization for final design/manufacturing configuration included factory simulations and hardware demonstrations. These efforts and other optimization tasks were instrumental in reducing cost by 18% and weight by 45% relative to an aluminum baseline. The qualitative and quantitative results of the manufacturing demonstrations were used to assess manufacturing risks and technology readiness.

### INTRODUCTION

Under the NASA/ Boeing Advanced Technology Composite Aircraft Structures (ATCAS) program, design / process trade studies were performed using low cost manufacturing technology for a 15 ft. by 31 ft. crown panel. Through a down selection process which incorporated the DBT approach, several design configurations, representing efficient manufacturing processes, were evaluated. Detailed costs and manufacturing requirements were established for six crown panel configurations. The best combination of stringers, frames, and skin for weight, cost, and performance were chosen as the global design (Refs. 2 and 3). Further optimization of the selected intricate bond design was conducted with structural performance analysis, cost optimization software, manufacturing hardware demonstrations, and tests. Throughout the local optimization process, DBT efforts ensured that the final design complied with all criteria (structural, manufacturing, design, etc.).

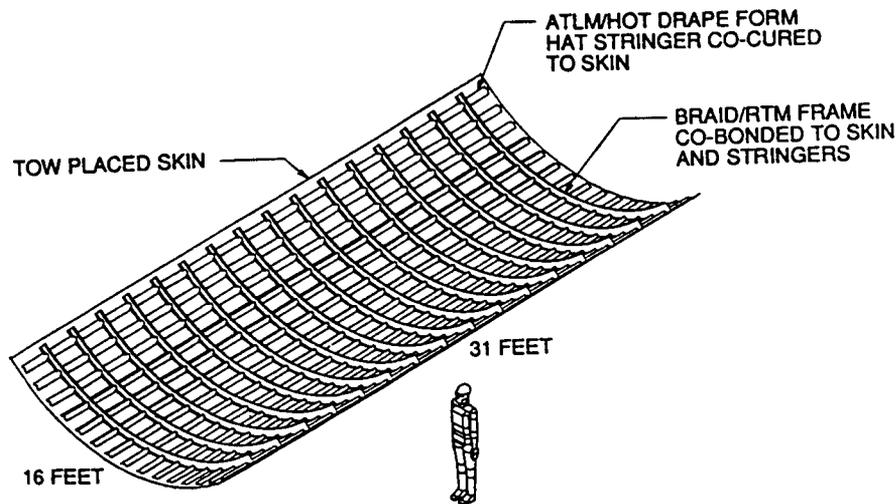
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**Figure 1: Flow Chart of Crown Panel Optimization Process**

The global design configuration shown in Figure 2 represents key cost effective processes used for the intricate bond design. When evaluating the manufacturing cost of large aluminum structure, costs drivers that could be minimized with composite materials were identified and targeted for reduction (Ref. 4). These cost centers include; 1) minimize labor intensive shimming and fasteners installation by producing large elements and assemble using co-curing/co-bonding operations, 2) automate and control processes to reduce inspection while increasing production efficiencies, 3) use automated equipment that efficiently produces quality structure with low cost material forms, and 4) increase part size and commonality as indicated in Figure 3. Since the intricate bond panel is very stiff, assembly issues must be addressed in all phases of process and tooling developments to minimize panel warpage and maximize panel dimensional accuracy.



**Figure 2: Global Intricate Bond Configuration**

	<i>Aluminum</i>		<i>Composite (Global Evaluation)</i>		<i>Composite (Local Optimized)</i>	
	<u>Number</u>	<u>Types</u>	<u>Number</u>	<u>Types</u>	<u>Number</u>	<u>Types</u>
<i>Skin</i>	3	3	1	1	1	1
<i>Frame</i>	16	3	16	3	16	1
<i>Stingers</i>	23	5	15	5	11	2
<i>Clips</i>	368	5	0		0	
<i>Fasteners*</i>	11,770		0		0	

\* Fasteners for quadrant panel assembly not included

Figure 3: Comparison of Crown Panel Elements

### Global Manufacturing Plans

The global evaluated crown panel configuration used the cost advantages of the ATP, braiding/resin transfer molding and unique bonding of skin, stringer, and frames with innovative tooling as shown in Figure 4 (Refs. 3 and 4). The skins are produced four at a time to maximize cost advantage for tooling and labor. The resin transfer molded 16 ft. long frames were produced sixteen at a time to realize the same benefits. The stringers were fabricated with an over-head gantry ATP to take advantage of the cheaper tow material form and batch sizes. The global crown panel design dictated a reverse assembly process, which required a rotisserie to assemble the frames and stringers and then transfer the subassembly onto the skin. Challenges for the reverse assembly process and cure tooling required unique concepts and tooling developments to minimize risk and cost. The reduction of cost and risk were realized in the local optimization process through hardware demonstrations.

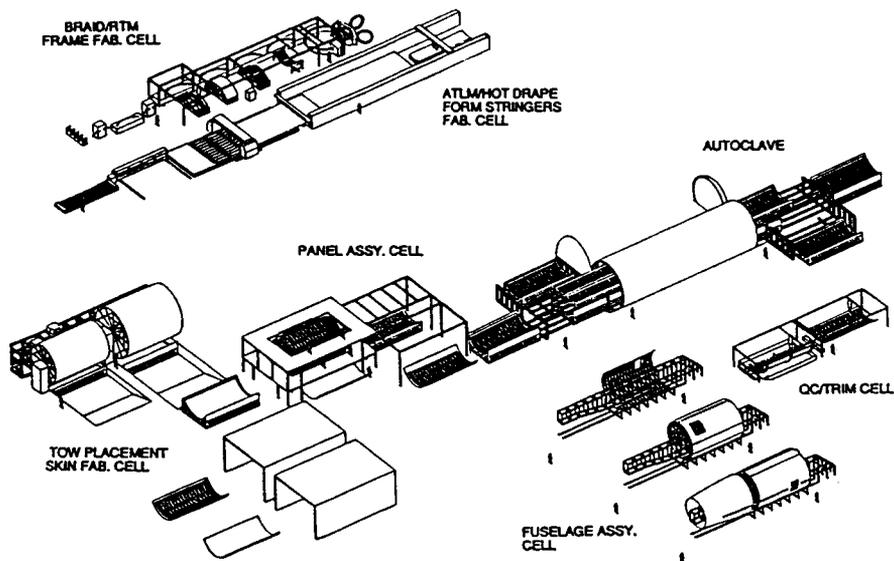
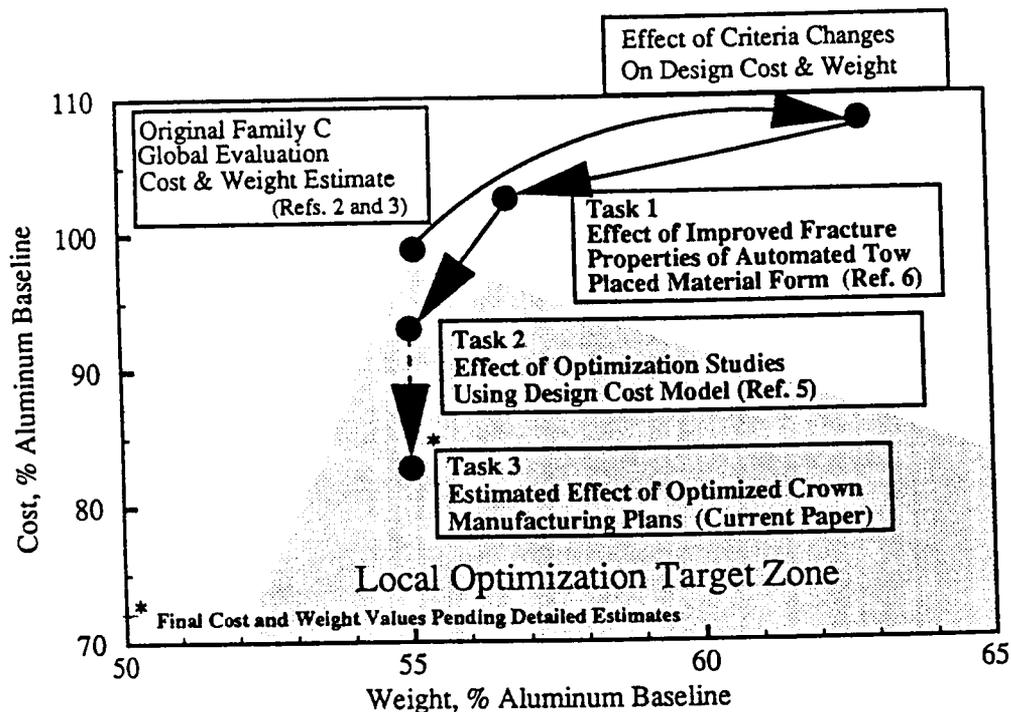


Figure 4: Factory of Global Configuration

## Local Manufacturing Optimization

Figure 5 shows the history of the intricate bond design from global selection through local optimization. Once the cost data for global intricate bond configuration was established, further optimization was conducted through several tasks. Design requirements were reviewed and the initial global point was shifted to reflect an increase in weight to meet changes in criteria (Ref. 5). The efforts of task 1 increased weight savings with improved fracture toughness of tow placed material forms (Ref. 6). Cost and weight were further reduced with the aid of software which optimized cost and weight based on known manufacturing cost relationships and structural performance criteria (Ref. 5). The current software optimization is based on known manufacturing processes selected for a particular design and is not capable of selecting an alternative lower cost process for a given design variation. These types of qualitative manufacturing process selections were assessed for further cost benefits through manufacturing demonstrations and factory simulations. The hardware demonstration and factory simulations were also used to verify and reduce cost of each manufacturing process, assess / minimize manufacturing risks, and conduct tests to verify structural performance. Under task three, the manufacturing hardware demonstrations and factory simulation reduced cost an additional 10.7%.

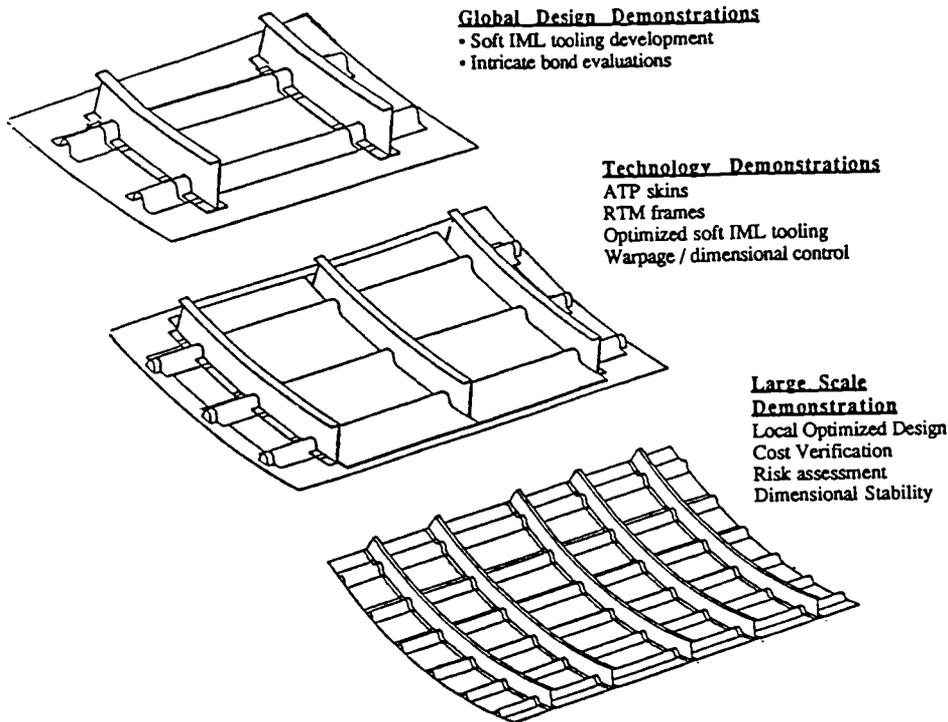


**Figure 5: Effects of the Criteria, Material Properties, Design Details, and Manufacturing Processes on the ATCAS Crown Panel Local Optimization**

## Manufacturing Hardware Demonstrations

To meet ATCAS program objectives, large manufacturing demonstration panels were identified to access manufacturing risk, technology readiness for the intricate bond configuration, and verify cost for an optimized configuration. New innovative cure tooling concepts, which were critical to the success and cost reduction of the intricate bond configuration, were optimized through a series of tool trials to not only reduce manufacturing risk but to increase the part quality / performance. Scale-up issues were considered such that manufacturing concepts demonstrated on small panels

would accommodate large panels without increasing manufacturing risks. Several types of manufacturing demonstration panels were identified to validate the tooling and intricate bond process ( Figure 6). First, two-frame/two stringers flat and curved panels were fabricated at Boeing to develop the soft IML tooling concept. The results were used to fabricate 3 ft. by 5 ft. panels at Hercules to evaluate the technology integration of the ATP skins and stringers, RTM frames, and innovative soft IML tooling. Tooling and manufacturing processes modifications from these trials support the large scale demonstrations.



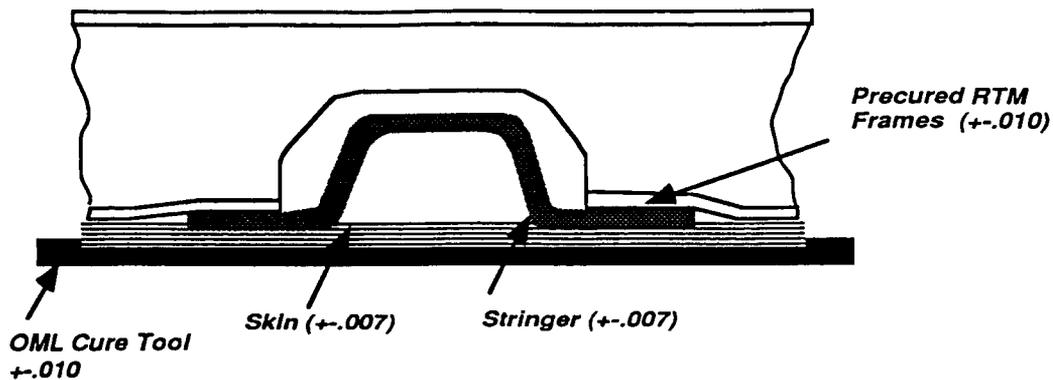
**Figure 6: Series of Manufacturing Demonstrations to Validate Local Optimization**

One of the main challenges of the selected global crown panel was to ensure bond integrity of a precured frame cobonded with a green skin and stringer on a contoured surface. The capability to cobond precured frames onto a contoured surface may eliminate fasteners, but the risk to control tolerance build-up and part location for subsequential assembly is increased. Figure 7 shows the tolerances associated with each structural element for the intricate bond configuration.

It is evident that either a clearance or interference situation may occur. Since these conditions are too costly to control with precise machining or manufacturing methods, the manufacturing trials assessed the ability of the adhesive and uncured skin and stringer material to flow and accommodate either condition with the aid of soft IML tooling.

### **Intricate Bond Tooling Considerations**

The success of the intricate bond also depends on the tooling material and tool contour accuracy to minimize gaps and interference between elements, control panel warpage, and reduce production maintenance. One main consideration for the type of tooling used to fabricate the intricate bond panel is the compatibility of the OML cure tool, stringer tooling, and resin transfer mold for frames. If the same tooling material is used for both the OML cure tool and frame tool, then the skin and



**Figure 7: Intricate Bond Element Tolerances**

precured frame mismatch during cure is minimized. Invar 36<sup>2</sup> was selected as the material for the hard tooling because the coefficient of thermal expansion (CTE) is very close to that of the composite laminate (1.7 in/in./ F°). Since Invar 36 can be machined with precision by typical machining operations master tooling, which is typical for composite tools, is eliminated. The reusable stringer cure tooling had to accommodate skin thickness variations and be extractable after cure. Therefore, silicon mandrels were originally selected for stringer tooling. To avoid the typical labor intensive bagging procedures and risks associated with bag failures, soft IML reusable tooling was developed. The soft tooling was required to assist in locating elements during panel assembly and control resin bleeding.

### **Manufacturing Demonstration of Soft Tooling**

The first demonstration panel was fabricated to develop the reusable net shape soft IML tooling concept and to evaluate the reverse assembly process. The flat two stringer / two frame panel was constructed of precured fabric frames, tape hand laid skin, and drape formed stringers. Variations of frame mandrel inserts and no frame mandrel inserts were evaluated as shown in Figure 8. To make a net shape soft IML tool, a mock-up of the stringer-frame-skin panel was constructed. Next, calendered flouroelastomer material, reinforced with graphite cloth for thermal stability, was placed on the mock-up surface and cured. The continuous flouroelastomer bag has integral vacuum ports and breathing paths to avoid volatile entrapment. Silicon frame mandrels were fabricated and used to provide support to one of the frames during final cure. To transfer autoclave pressure to the stringer in the mouse hole area and prevent resin pooling, pressure pads that mated with the flouroelastomer bag were inserted.

To assemble the panel for cure, precured frames and mandrel inserts were located into the soft IML tool cavities. Adhesive was placed along the base of the frame and then the uncured drape formed stringer charges and silicon cure mandrels were located into the soft IML tool. The skin and cure caul plate were then placed on the frame / stringer subassembly.

The soft IML tool produced a net shape surface and controlled resin flow as shown in Figure 9. Pressure pads were successful in preventing the resin bleed in the mouse hole areas and provided pressure to cure the stringer section directly underneath the frame.

<sup>2</sup> Invar 36 is a steel with 36% nickel content produced by Inconol Inc.

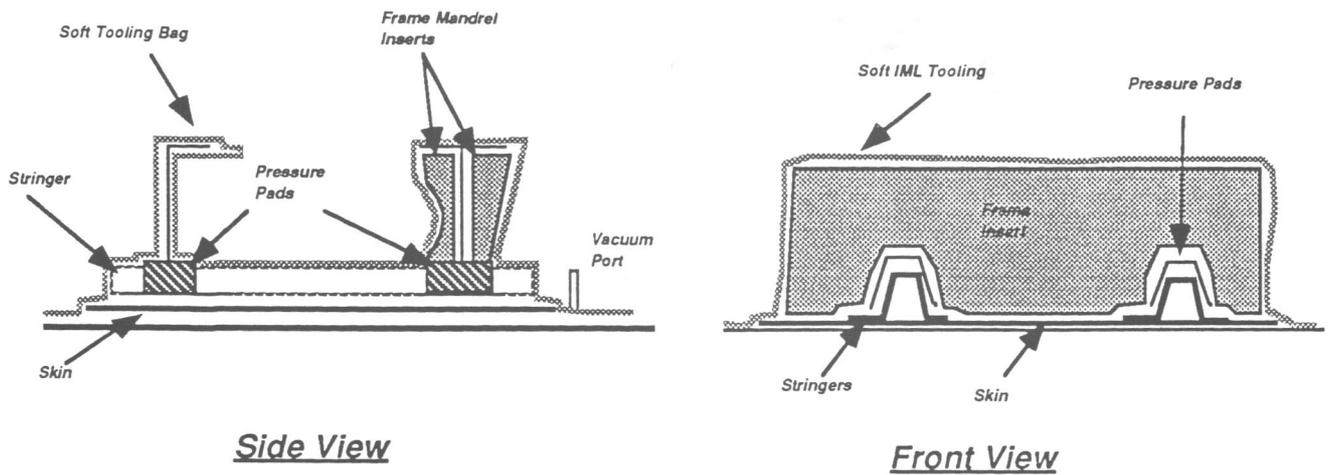


Figure 8: First IML Soft Tooling Configuration

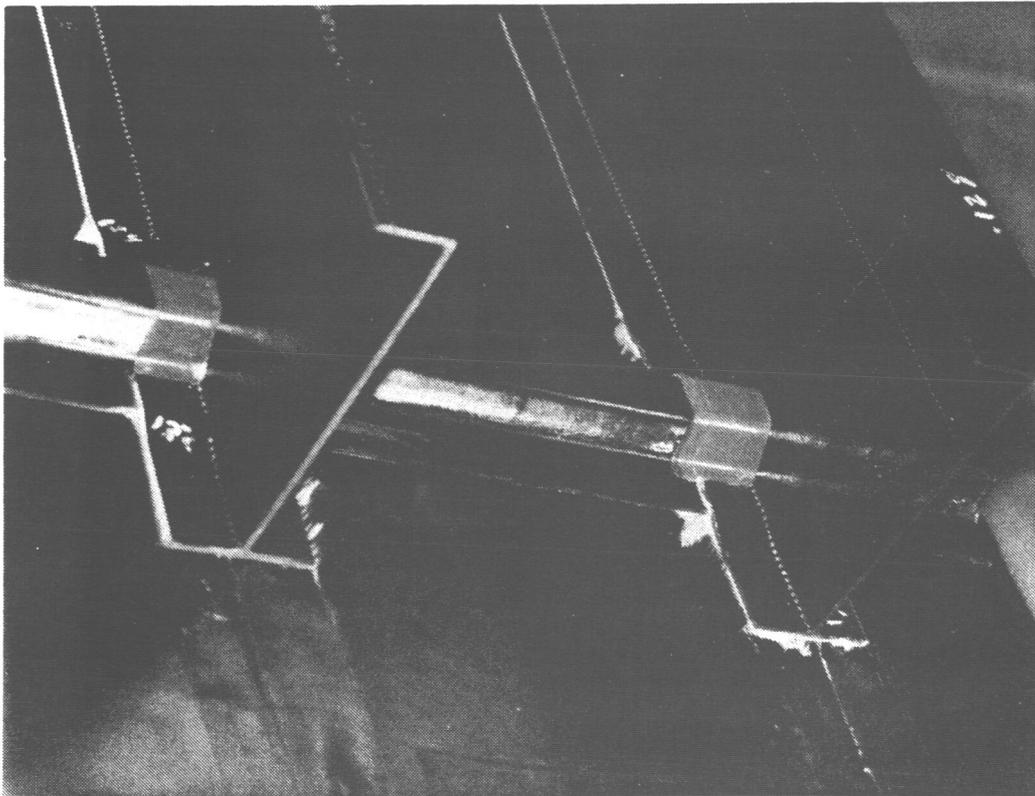
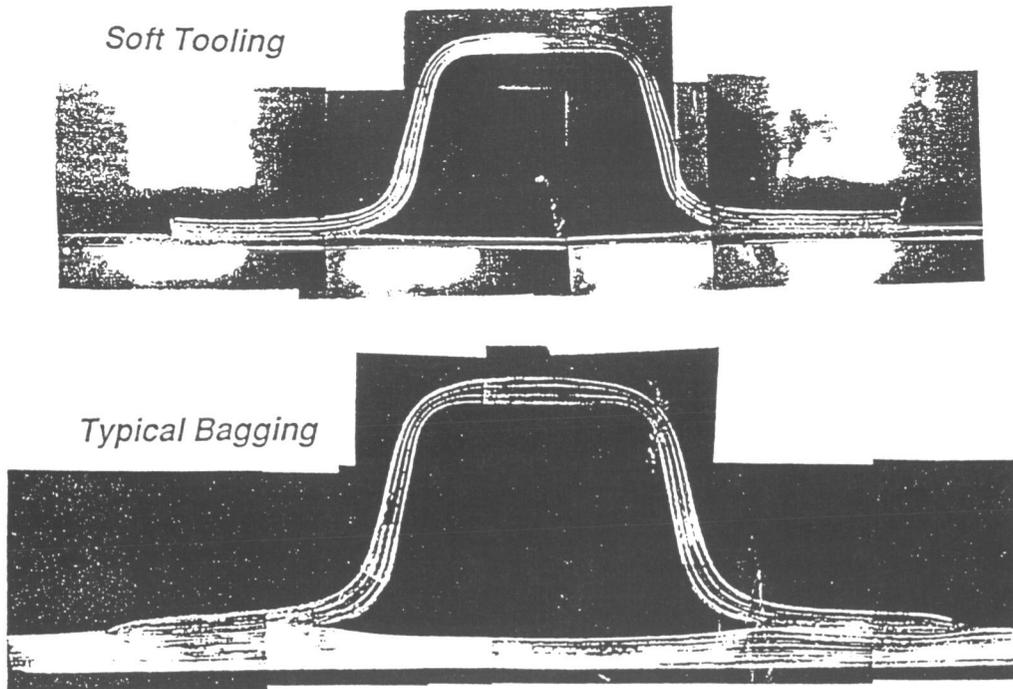


Figure 9: Cure Panel with Soft IML Tooling

Inspection of the panel indicated a good bond line with small voids caused by improper nesting of the soft IML tooling near the frame base flanges. The adhesive, skin, and stinger material did flow as expected to compensate for the interference/gap condition of the stringer-frame intersections. The soft IML tooling also trapped resin from bleeding up onto the frame flanges. A cross section of the stringers indicated that more stringer wall thickness control was achieved with the soft IML tooling when compared to a typical bagging process as shown in Figure 10.



**Figure 10: Stringer Effects of Soft IML Tooling and Typical Bagging Approach**

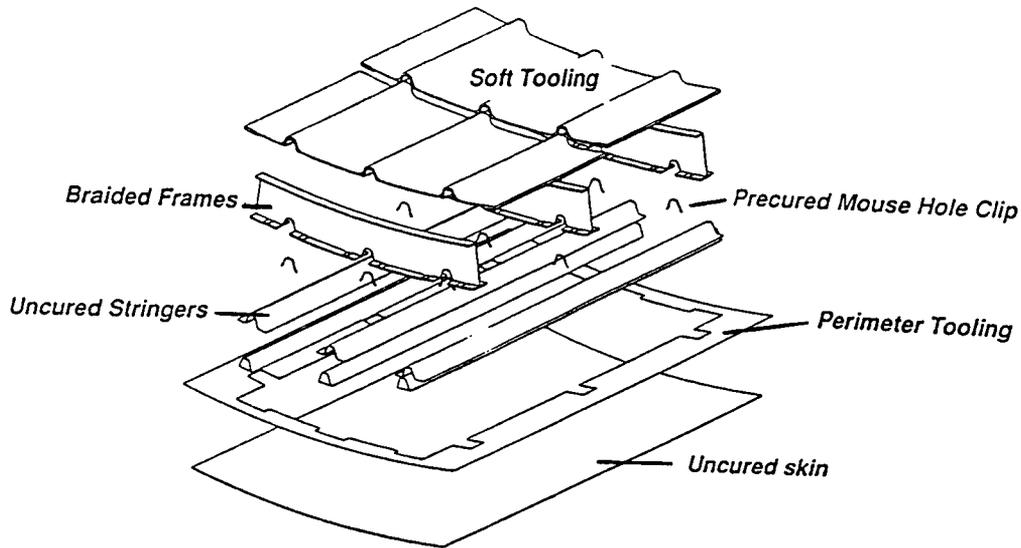
During and after the demonstration of the reversible assembly process with the soft IML tooling, problems were identified that required additional tooling modifications. Table 1 indicates the problems and solutions that were verified on the second tooling trial demonstration.

<i>Problem</i>	<i>Solution</i>
Difficult to manage one piece bag. Fit of multiple large parts with soft IML tooling bag is difficult.	Develop a two piece system 1. a continuous silicon bag for the cure bag 2. separate fluoroelastomer soft IML tooling for each frame bay
Parts did not nest properly with IML soft tooling causing resin pooling and cure pressure variations.	Taper the frame and stinger flanges to avoid tooling interference.
Mouse hole pressure pads can be misplaced easily causing resin rich areas or stringer tooling depressions.	Eliminate pressure pads with fly-away tooling.
The uncontrolled expansion of the stringer cure mandrels produced stringer thickness variations.	Develop a low CTE flexible extractable mandrel
Thickness variations of the soft IML tooling produced surface resin rich areas.	Construct soft IML tooling with uniform thickness

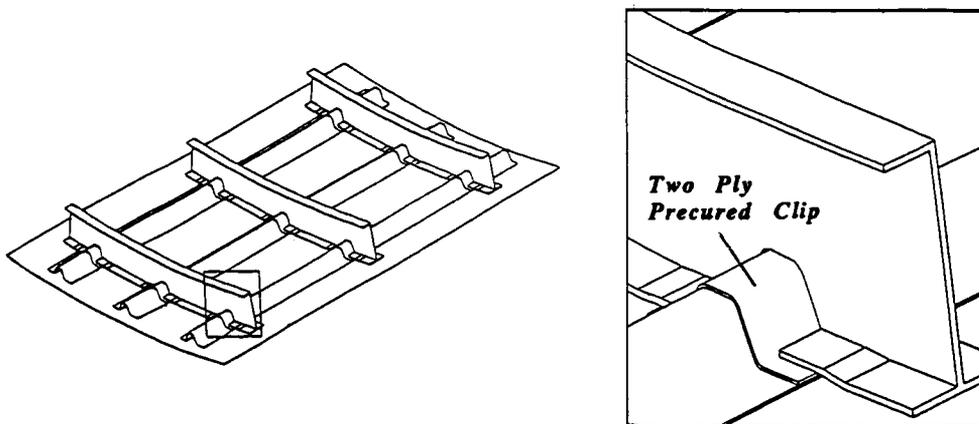
**Table 1: Results and Solutions for the Development of Soft IML Tooling**

## Optimization of the Soft Tooling Concept

A two piece soft IML tooling system was designed to meet the global assembly requirements. This concept involves the use of segmented soft IML tooling between each frame and a near net shape continuous silicon cure bag that covers the whole assembly (Figure 11). The silicon bag is textured so that there is a continuous air path across the panel. The mouse hole pressure pads were replaced with a two-ply precured hat shaped clip as shown in Figure 12. The clip accomplishes the same tooling requirements, but remains as part of the structure. The clip extends underneath the frame sections and beyond the edge of the frames so that resin is trapped and not permitted to bleed into the mouse hole area. The new clip concept not only reduced the number and complexity of the soft IML tooling, but eliminated the manual labor associated with locating the pressure pads. The revised soft IML tooling still retained the cost advantage by eliminating recurring bagging material (i.e. breather, separator film, etc.).



**Figure 11: Revised Soft IML Tooling Concept**



**Figure 12: Mouse Hole Clip Configuration**

To minimize the stringer gage thickness variations, a low CTE flexible mandrel was developed. The flexible mandrel is comprised of thin laminates constrained to flex only along the length of the mandrel. The mandrel is encapsulated with a silicon tube to prevent resin bleed between the laminates and aid in mandrel extraction.

### Demonstration of the Revised Soft IML Tooling

The second tooling trial was used to verify the new tooling concept with a curved panel. Since the large cure tool for the 3 ft. by 5 ft. and 7 ft. by 10 ft. panels was not completed, an existing steel 76 in. radius tool was used to cure a two frame / two stringer panel. The soft IML tooling was fabricated with a flat mock-up rather than a curved mock-up since the tooling is flexible enough to accommodate the radius bend without increasing manufacturing risks. The tooling trial included frames that were constructed of fabric and precured on steel tooling. After the panel was assembled onto the OML cure tool, a gap of 0.020" between the frames and skin was detected. This was attributed to a partially debulked skin and stringer lay-ups. To ensure that the skin, stringer, and frames were completely bonded without gaps, a 150 psi cure pressure was used. Figure 13 shows the cured panel and soft IML tooling used between frames. Point A is the soft IML tooling that is located between frames; point B is the silicon stringer cure mandrel, and point C is the new low CTE flexible stringer mandrel.

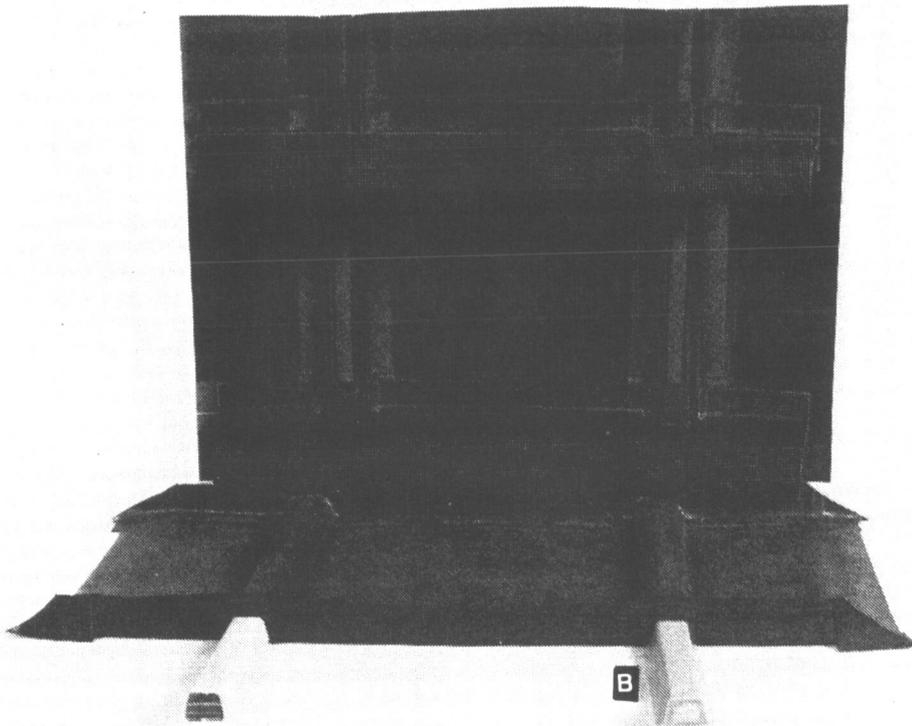


Figure 13: Intricate Bond Panel and Soft IML Tooling

Visual inspection of the panel showed that the IML soft tooling imparted a smooth net shape surface. Some resin pooling occurred along the non-tapered frame flange due to a gap between the soft IML tooling and frame flange. The fly-away mouse hole clip tooling performed as expected but some resin bled into the mouse hole area due to an error in the mock-up tool used to fabricate the soft IML tooling. The panel was inspected with through transmission and pulse-echo ultrasonic methods. No porosity was indicated in the panel or bond interfaces. Further sectioning of the stringers and frames revealed a few small voids near the skin-frame-stringer intersection ( see Figure 14). Point A shows voids in the precured fabric frames. These voids were eliminated in the precured resin transfer molded frames. The microphotographs indicate that both skin-frame-stringer intersections showed signs of an under-fill condition (compare points B and C). The actual under-fill condition prior to cure is difficult to determine since some resin bled into the mouse hole area. The tapered stringer flanges conformed more naturally minimizing the degree of skin movement (point B). The stringers were slightly mislocated but compensated by tapered stringer flanges and flexibility of the soft IML tooling to minimize resin pooling and skin wrinkles (point D). The flexibility of the soft IML tooling did not prevent resin bleeding of the non-tapered stringer flange (point E). Further inspection of the stringer cross section indicates that the low CTE flexible mandrel minimized the thickness variations and skin thinning under the hat stringer (compare points F and G). Point H shows a laminate wrinkle caused by an oversized radius filler. Although the flexible mandrel requires radius fillers that increase cost, the risk to extract the mandrel without damage is minimized.

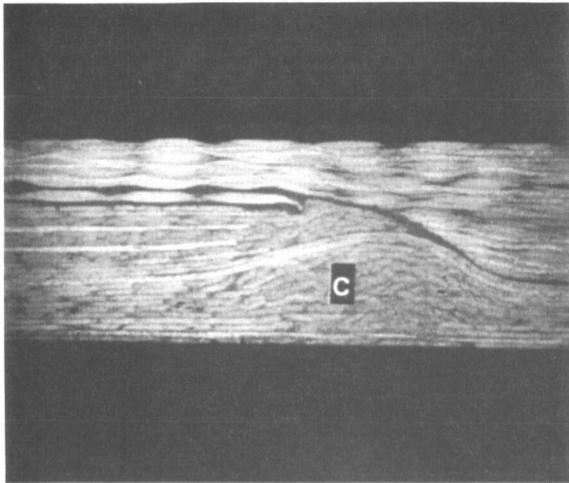
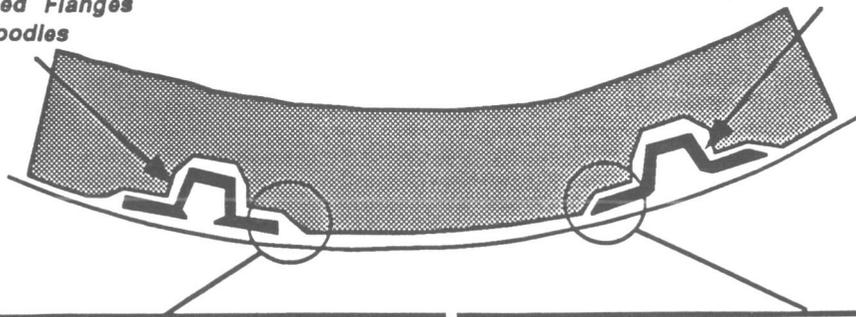
To fully address the assembly risks of the intricate bond design, causes and effects of panel warpage must be understood. During the development of the soft IML tooling, measurements were used to isolate causes of the panel warpage and minimize them through tooling modifications. Figure 15 shows transverse and longitudinal measurements from demonstration panels with and without frame elements.

Warpage data indicated that kinks in the panel occurred near the edges of the stringer flanges where resin pooling occurred. By tapering the stringer flanges and modifying the soft IML tooling, resin pooling on the outer flanges of the stringer was eliminated. Tooling changes and frame stiffening effects minimized the transverse panel warpage to 0.035 inch. Longitudinal warpage was minimized to 0.015 inch. Without the soft IML tooling and frame stiffening effects, larger deviations for a simple hat stiffened panel will occur.

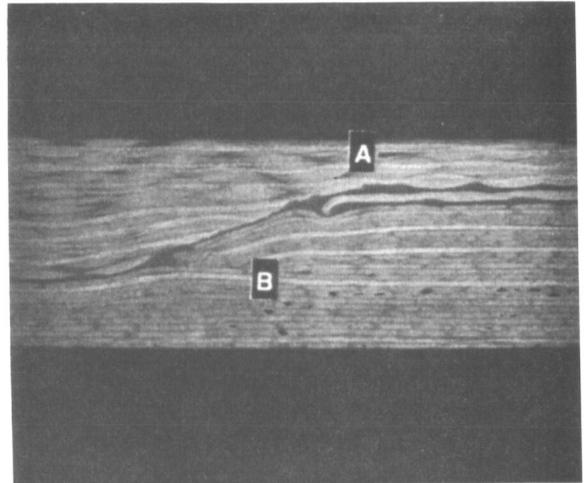
The revised soft tooling trial demonstrated that tapers on all stringers and frames are required to minimize the manufacturing anomalies with soft IML tooling. The low CTE flexible stringer mandrel controlled stringer and skin resin flow which is critical to minimizing panel warpage. The results of these tooling demonstrations will support the fabrication of the 3 ft. by 5 ft. and 7 ft. by 10 ft. intricate bond demonstration panels.

- Low CTE Cure Mandrel
- Non-tapered Flanges
- Radius Noodles

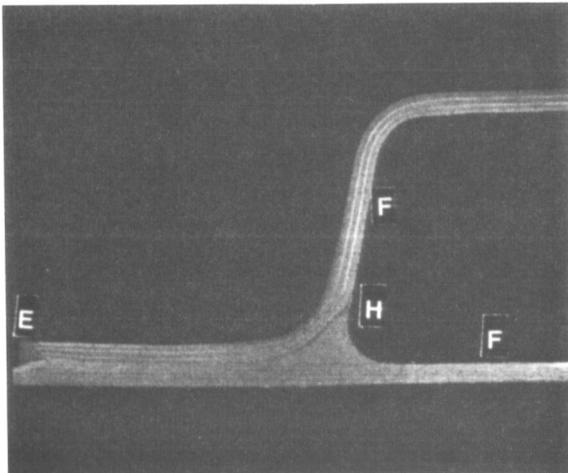
- Silicon Cure Mandrel
- Tapered Flanges



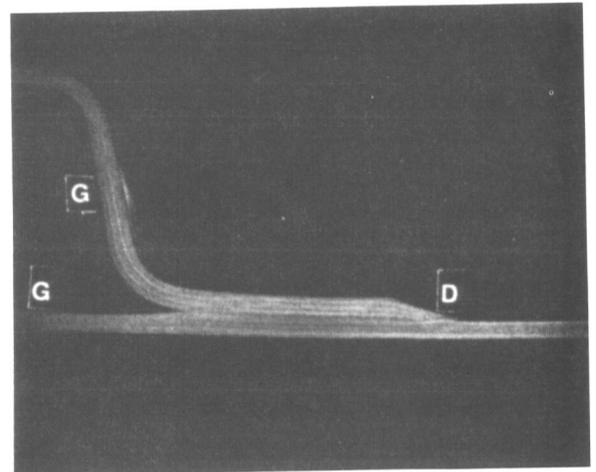
*Skin-Stringer-Frame Intersection*



*Skin-Stringer-Frame Intersection*

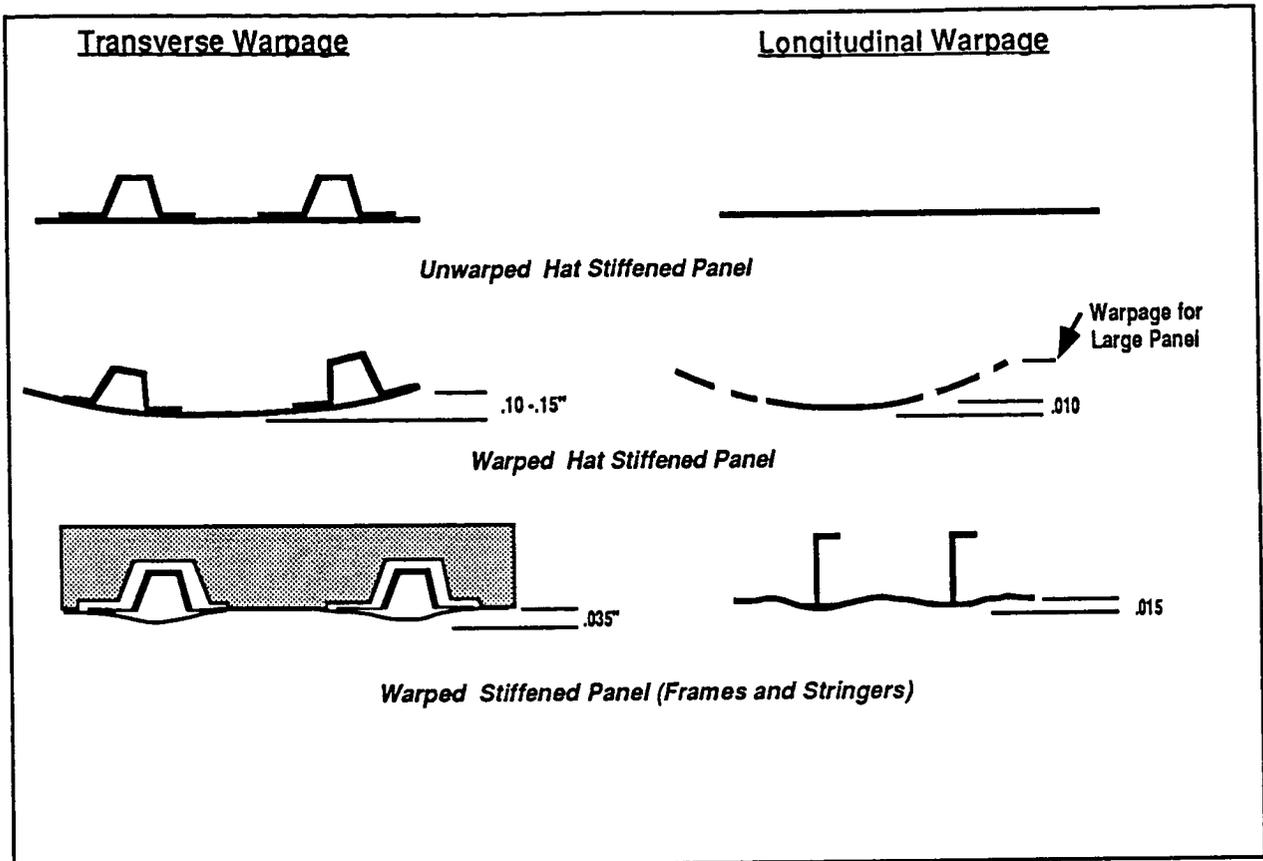


*Low CTE Flexible Mandrel*



*Low CTE Flexible Mandrel*

**Figure 14: Inspection of the Composite Panel Using the Revised Soft IML Tooling Concepts**

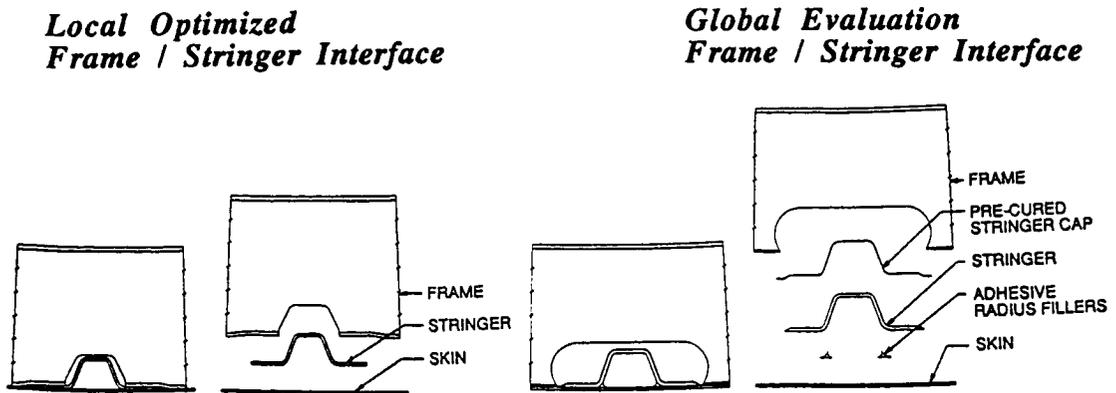


\* Illustrations exaggerate the warpage anomalies only for visual depiction

**Figure 15: Panel Warpage of Manufacturing Demonstrations**

**Local Optimization / Demonstration**

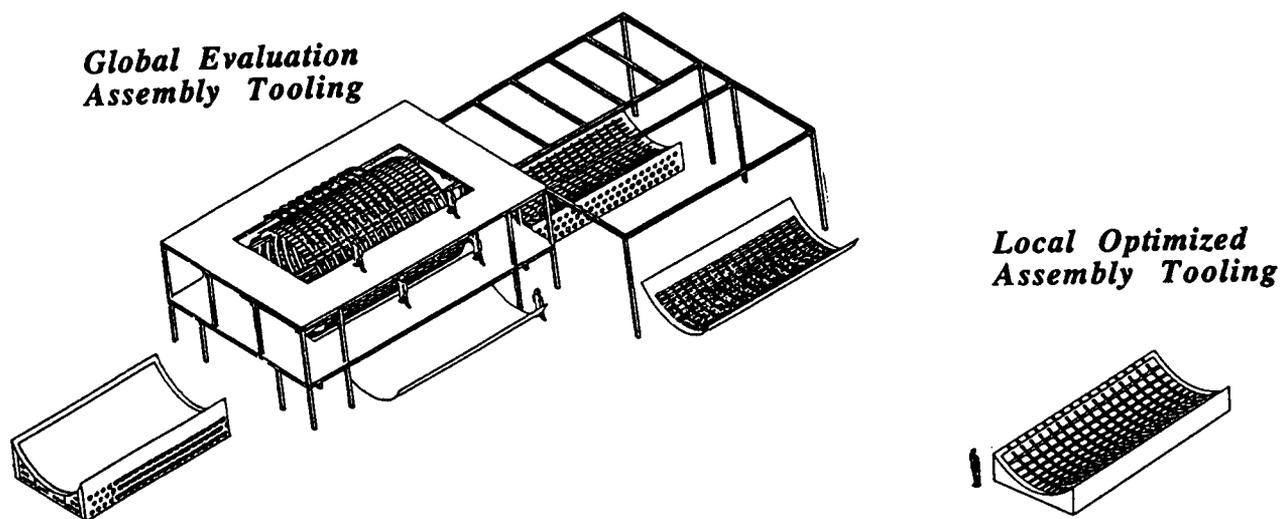
During the local optimization process for the intricate bond configuration, manufacturing costs and risks were assessed and several design modifications were identified for additional cost benefits. One of the most significant modifications was a larger frame mouse hole (see Figure 16) that reduced tolerance build-up at the stringers-frame-skin interfaces and opportunities for lower cost assembly methods could now be utilized.



**Figure 16: Mouse Hole Designs**

The reverse assembly method for the global configuration was driven by the fact that the mouse hole size restricted the ability to place frames on a preassembled skin-stringer panel. The larger mouse hole eliminates this restriction and a new panel assembly method was evaluated. Assembly costs were reduced by eliminating the need for the rotisserie assembly tool. Initial design assessment of the new mouse hole configuration reduced the frame weight by 8.5% without increasing the cost. The DBT determined that the modification to a larger mouse hole would require further testing to evaluate the structural performance impact.

The optimized panel is assembled on the OML cure tool with clamps to locate and secure the frames for cure. First, the skin and stringers are located onto the OML cure tool. Then the frames are located and clamped. The frame clamp design is critical so that the frames are only constrained to maintain frame spacing. The inability of the frames to adjust to skin and stringer debulking during cure may increase the risk of bond line voids due to inadequate skin cure pressure. Therefore, the clamps were designed with two degrees of freedom to eliminate these risks. The new assembly method as shown in Figure 17 not only reduced the number of assembly tools, but reduced manufacturing risks by eliminating panel assembly transfers and potential high risk factory flow problems.

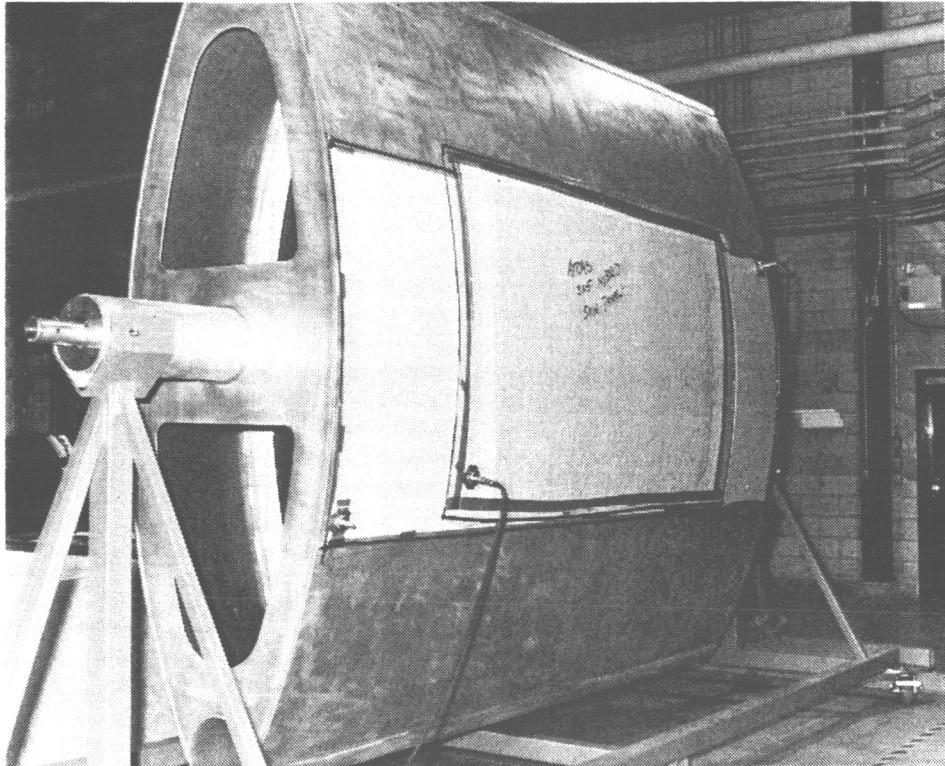


**Figure 17: Comparison of the Global and Local Panel Assembly Tooling**

The new mouse hole and finalized soft IML tooling configuration was demonstrated on a two frame / three stringer curved panel. The panel included resin transfer molded triaxial braided frames with a 20° tapered flange. The frame fabrication procedures were optimized by Boeing and Fiber Innovations and are summarized in reference 7.

## Demonstration of Key Low Cost Manufacturing Technologies

The local optimization key manufacturing technologies were integrated and demonstrated with the fabrication of two 3 ft. by 5 ft. panels. For proper verification of the optimized manufacturing plans, critical tooling for skin fabrication and cure of the intricate bond assembly were designed and constructed. A winding mandrel was designed for parts up to 10 ft. by 14 ft. long and was constructed with aluminum to minimize weight. To demonstrate the tow placement of multiple large skins, a double lobed mandrel was designed to meet the ATP work space limitations (see Figure 18).



**Figure 18: ATP 122" Radius Winding Mandrel**

The OML cure tool for 3 ft. by 5 ft. and 7 ft. by 10 ft. demonstration panels was designed by Hercules and Boeing and fabricated by Ebco, Vancouver, B.C. with Invar 36 material. The skin gage is 3/4 inches and the support structure is 3/8 inches thick. Since Invar 36 material has a lower heat up rate than steel or composite, the support structure was designed with large air passages to increase heat transfer by convection. This has been proven to be very effective in reducing tool weight without sacrificing rigidity critical for tool dimensional stability. To ensure tool quality, Boeing used a computerized advanced theodolite system (CATS) to measure the surface irregularities as shown in Figure 19. About 250 points on the tool surface were digitized and compared to a cylindrical surface of a 12 inch radius. The standard deviation was  $\pm 0.007$  inch which satisfies the requirement of  $\pm 0.010$  inches.

### Local Optimized Fabrication Demonstration

The two 3 ft. by 5 ft. demonstration panels were fabricated as part of the scale-up process for the final crown 7 ft. by 10 ft. demonstration panels. One of the 3 ft. by 5 ft. panels was constructed

with a hybrid material form consisting of 25% S-2 glass and 75% AS4 fiber. The skin and stringer charges were tow placed onto the double lobed winding mandrel and debulked (Figure 20). After the skins were wound with the 32 tow placement band head, the skins were placed into the Invar OML cure tool. The skin was oriented to the OML cure tool with the aid of a S-2 tow that was tow placed along the edge of the panel. The tow placed stringer charges were then trimmed and drape formed over the low CTE flexible mandrels. The stringers and cure tooling were then located onto the skin with the aid of a mylar template. The precured mouse hole clips and adhesive were then compacted onto the stringers at the frame-stringer intersection. Next, the three precured resin transfer molded frames were located and the soft IML tooling was placed between the frames. After the silicon bag had been secured and vacuum tested the panel was cured.

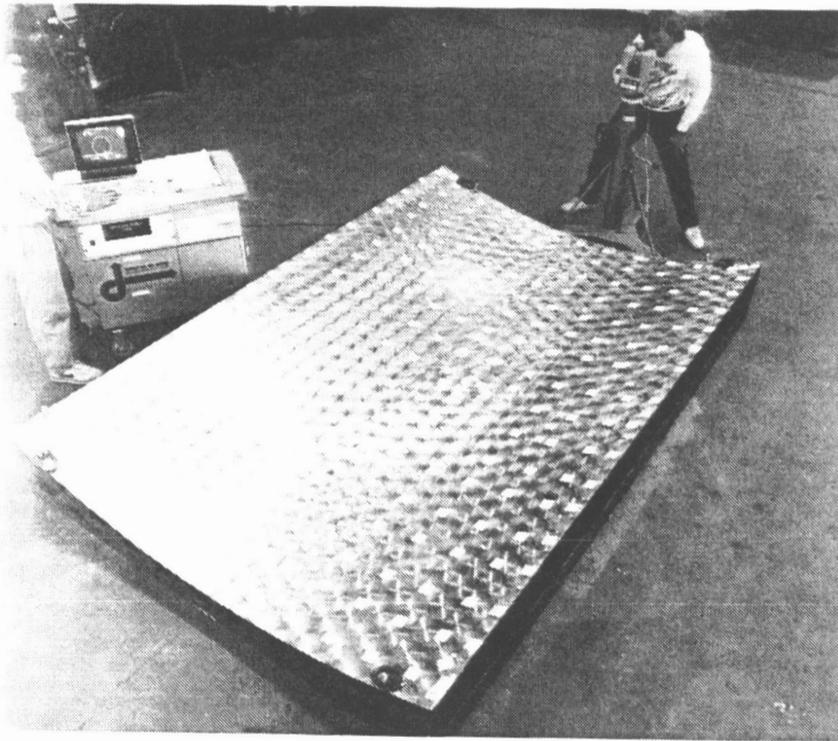


Figure 19: 122" Radius Invar Cure Tool

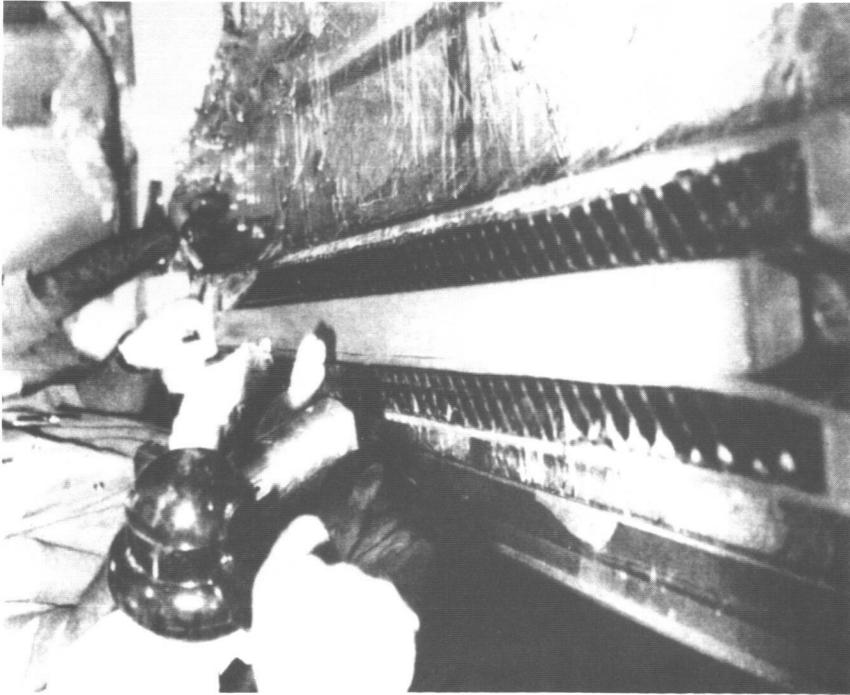


Figure 20 Stringer Drape Formed onto Mandrels

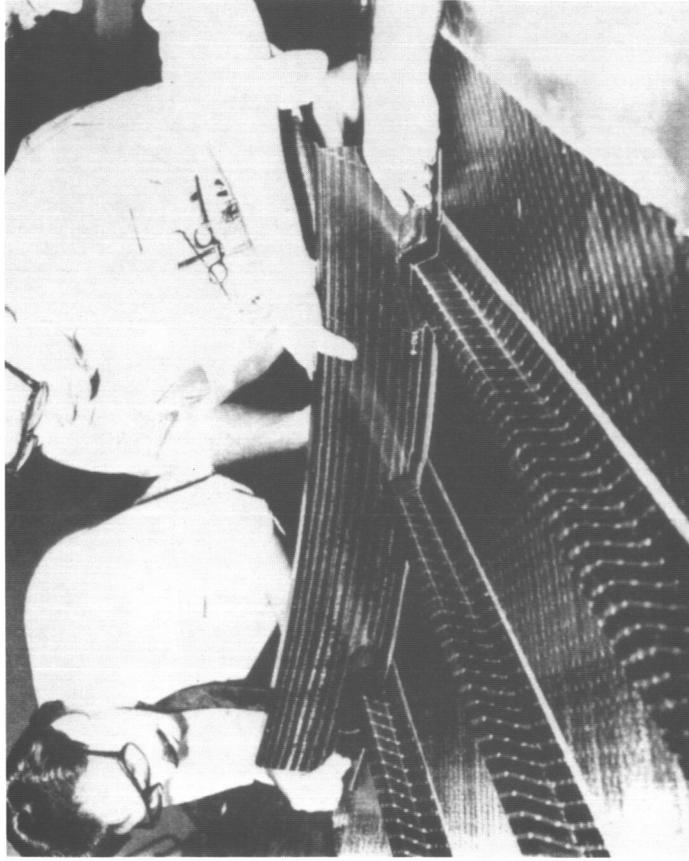


Figure 21 Locating Frames

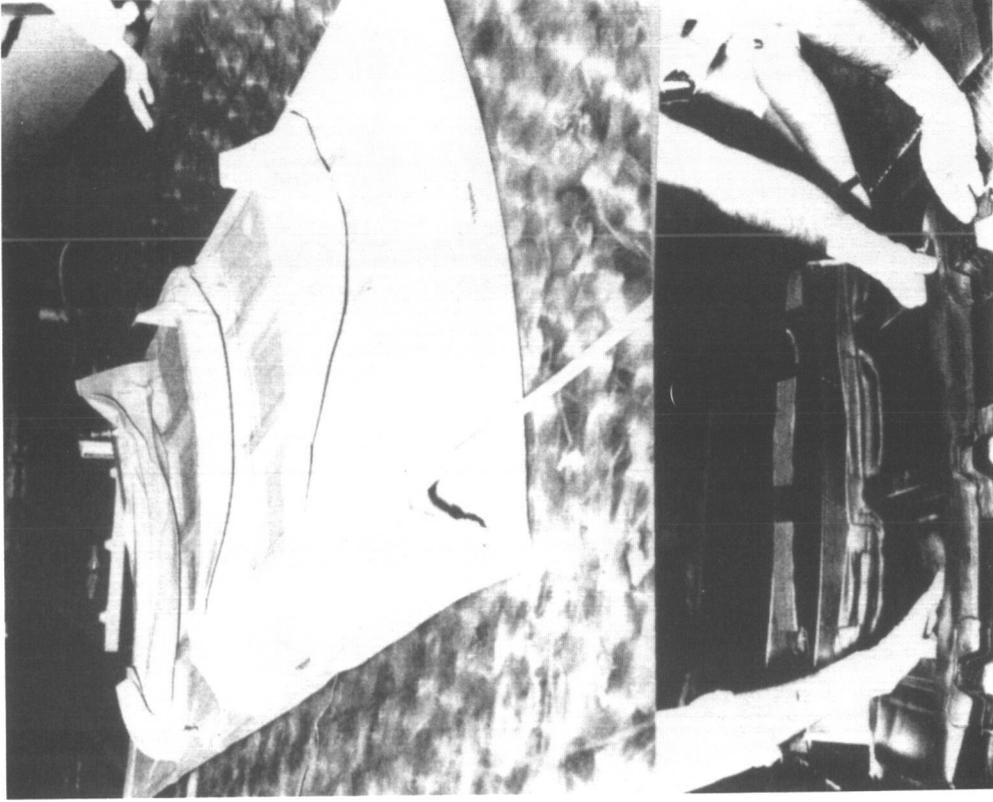


Figure 23 Placement of Silicon Cure Bag

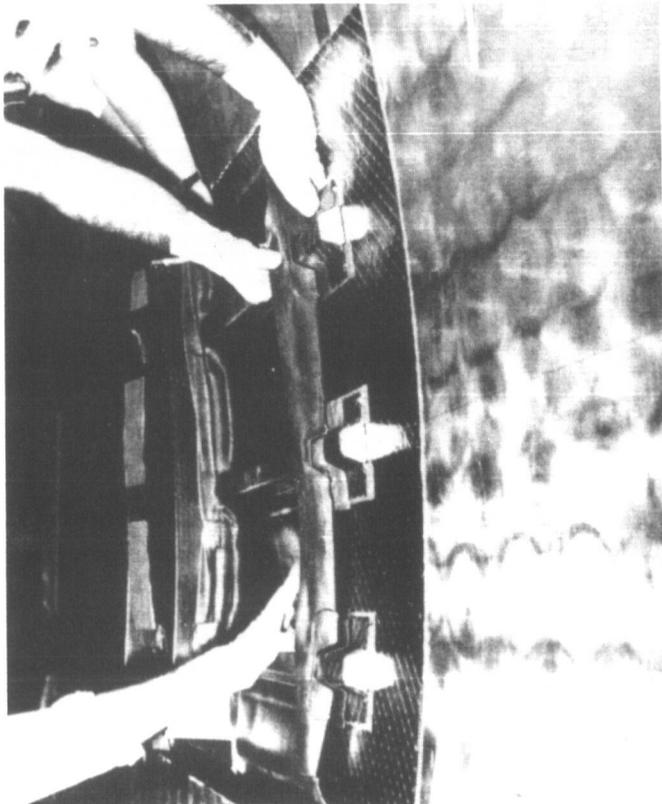


Figure 22 Locating Soft IML Tooling

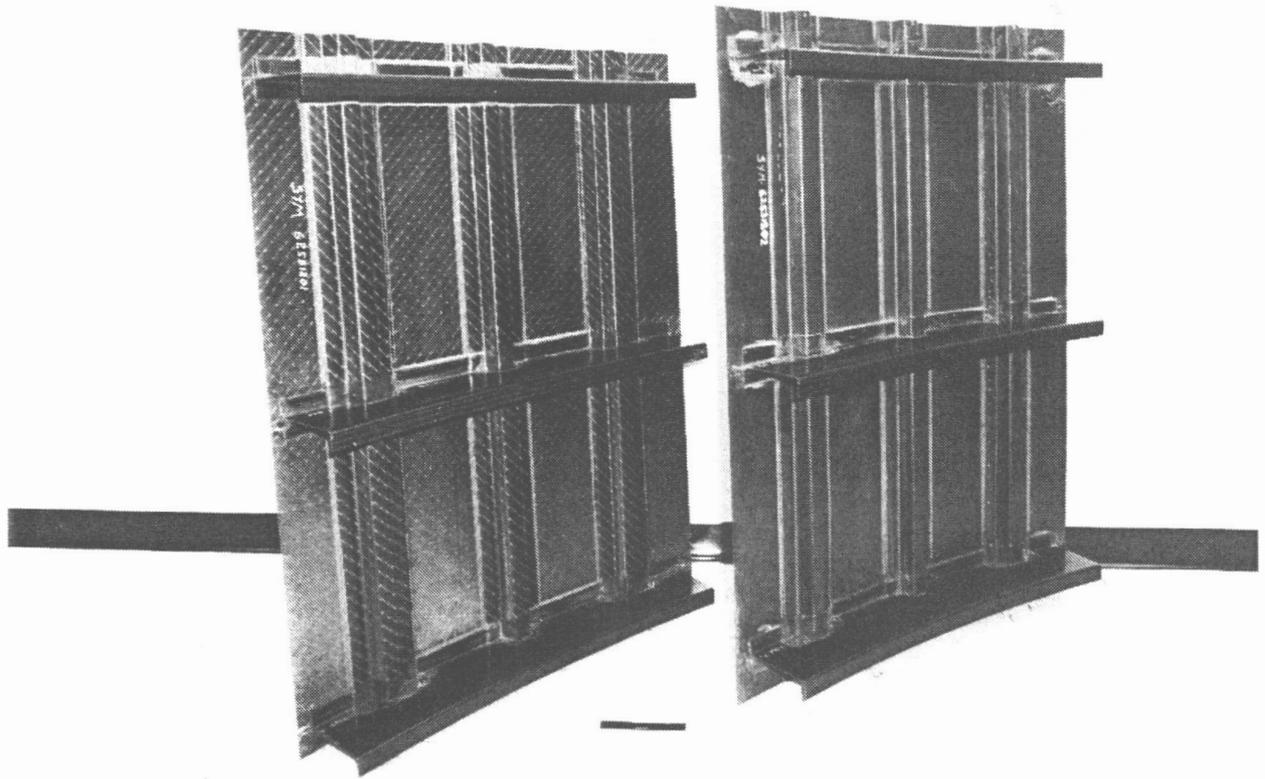


Figure 24 Cured Panels

## Cost Reduction by Manufacturing Demonstrations and Factory Simulation

Through the optimization process, the DBT minimized risk and cost for the intricate crown panel configuration. In conjunction with the manufacturing demonstrations, the factory was simulated for producing crown panels according to the NASA ACT ground rules (Ref. 1). The simulation process identified additional savings by optimizing tooling and batch sizes to reduce high risk factory flow problems. The following cost, weight, and risk savings represent the final local optimized design as shown in Figure 5.

Tables 2-4 represent the results of the local optimization process for the crown panel. The results of either design or manufacturing changes and how they impact cost, manufacturing risk and structural performance are summarized. It should be noted that additional optimization will be required beyond the local optimization which integrates the side and keel panel fabrication requirements.

### Cost Savings of Local Optimized Frames

A 30% savings in frame fabrication costs was realized from two major effects (see Table 2). One effect is the elimination of the bottom ply cap which reduced the number of preform elements and labor costs to fabricate and place (see Figure 25). The cap was initially a manufacturing criterion, but through the manufacturing demonstrations, its need was eliminated.

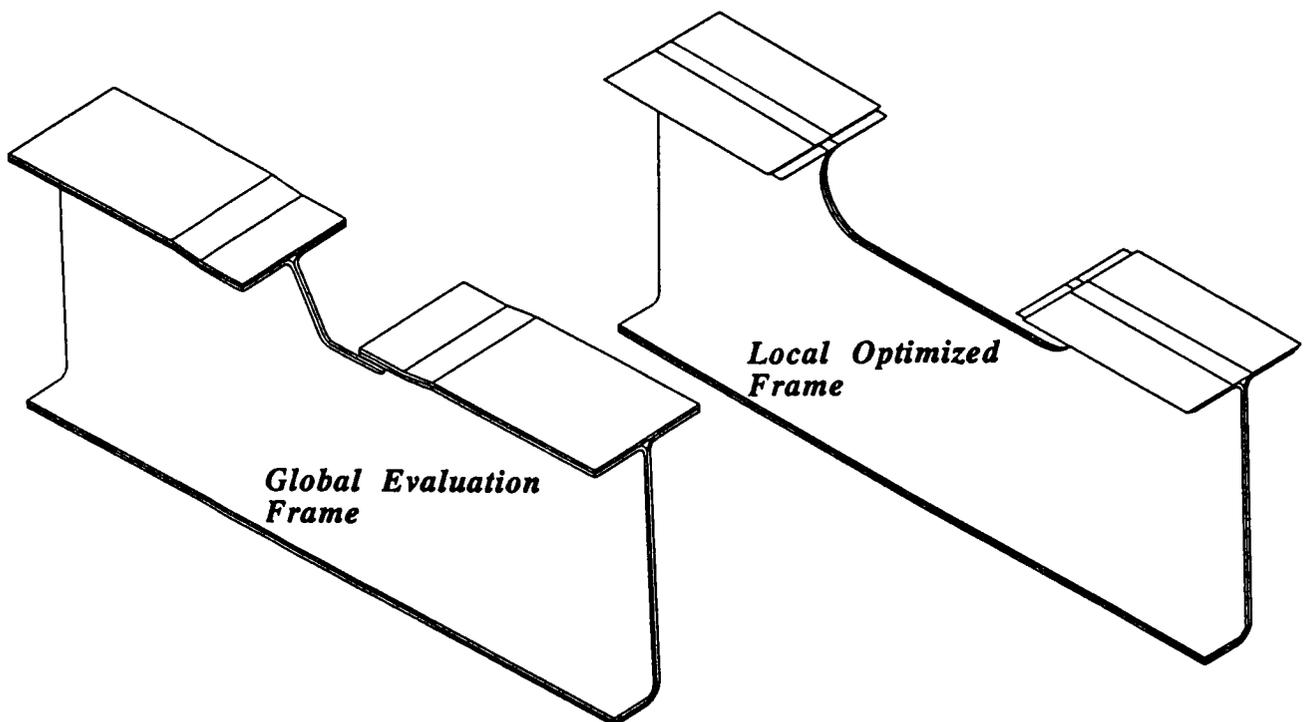


Figure 25: Global and Local Optimized Frame

The other major cost savings for the frames related to a reduction in tooling costs. Factory simulation results showed that sixteen RTM tools could be reduced to five and still meet the desired crown panel production rate. This reduced the total panel costs by 3.2% as indicated in Table 2. Some frame design modifications were identified that minimized manufacturing risks. Although costs saving were not projected for these modifications, risk of manufacturing anomalies were reduced.

<u>Global</u>	<u>Local</u>	<u>Purpose</u>	<u>Optimization Method</u>	<u>Impact</u>		
				Savings	Manuf. Risk	Struct. Perform.
Small Mouse Hole	Wider Mouse Hole	o Reduce tolerance build-up o Reduce tooling cost	- DBT - Demonstration	.6 %	Reduced	TBD
16 tools	5 tools	o Reduce tooling cost	-Factory Simulation	16.2 %	NA	NA
Bottom Cap	No Cap	o Increase Performance o Reduce cost o Reduce weight	- DBT - Demonstration	13.3 %	Reduced	Increased
Braided Noodle	Adhesive Noodle	o Increase damage tolerance	- Design Analysis - Demonstration	0 %	Reduced	Increased
Flange edge	Tapered Edge	o Minimize resin pools o Lower cure bagging risks o Increase pull-off strength	- Structural Tests - Demonstration	0 %	Reduced	Increased

**Total Frame Savings                      30.1%**

<b>Total Panel Savings</b>	<b>3.2 %</b>
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**Table 2: Savings of Local Optimized RTM / Braided Frames**

**Cost Savings of Optimized Panel Assembly/Cure**

One of the high risk areas identified with the crown panel configuration was the ability to bag and cure the frames, stringers, and skin together. The larger mouse hole design eliminated the rotisserie tool and allowed the use of the OML cure tool as an assembly tool. These changes reduced tooling costs, factory floor space, and the potential for factory flow problems. A panel assembly cost of 22.2% savings was gained which reduced the total panel cost by 4.9% (see Table 3).

<u>Global</u>	<u>Local</u>	<u>Purpose</u>	<u>Optimization Method</u>	<u>Impact</u>		
				Savings	Manuf. Risk	Struct. Perform.
1-piece reusable cure bag	2- piece Bag	o Reduce Labor costs o Reduce tooling costs o Robust for tolerance o Uniform Pressure control	- Factory Simulation - Demonstration	18.5 %	Reduced	Reduced anomalies
Reverse Panel Assembly	Assembly on OML cure tool	o Eliminate tooling o	-Design Optimizer -Factory Simulation	3.7%	Reduced	NA
Bag-frame stringers-skin	Skin-frames stringers-bag					

**Panel Assembly Savings                      22.2%**

<b>Total Panel Cost Savings</b>	<b>4.9%</b>
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**Table 3: Savings of Local Optimized Panel Assembly**

**Cost Savings of Optimized Skin and Stringers**

The major cost savings for stringers was accomplished by reducing the number of processing steps with the flexible low CTE mandrels and automated trimming operations. When the tow band width was increased from four inches to six inches, a 2.6% cost savings was realized for the skin and stringer fabrication costs. The stringer and skin cost savings was 17.8% which reduced the total crown panel cost by 2.2% as shown in Table 4. The combination of all cost savings generated a total panel savings of 10.7 % (Tables 2-4).

<u>Global</u>	<u>Local</u>	<u>Purpose</u>	<u>Optimization Method</u>	<u>Impact</u>		
				Savings	Manuf. Risk	Struct. Perform.
4" Tow band width	6" Tow band width	o Reduce Labor costs	Factory Simulation	Skins 2.6 %  Stringers 5.6%	Reduced	TBD
16 stringers	10 Stringers	see Ref. 5	-Design Optimizer -Factory Simulation	see Ref. 5	NA	NA
Manual Trimming	Automated trimming	o Reduce labor costs	- Factory Simulation - Demonstration	14.4 %	Reduced	NA
Stringer non-tapered edge	Tapered Edge	o Minimize resin pools o Lower cure bagging risks o Increase pull-off strength	- DBT - Demonstrations	0 %	Reduced	Increased
Rubber cure tooling	Flexible low CTE cure tooling	o Minimize resin pools o Lower cure bagging risks o Increase pull-off strength o Reduce tooling costs o Reduce processing steps o Increase part tolerance control	- Factory Simulation - Demonstration	.1 %	Reduced	Increased
Drape Forming	Optimized procedures	o Reduce processing steps o Optimize procedures	Simulation	3.3%	Reduced	NA

**Total Skin and Stringer Savings                      17.8 %**

<b>Total Panel Cost Savings</b>	<b>2.2 %</b>
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**Table 4: Savings of Local Optimized Skin and Stringers**

## Sensitivity Studies of the ATP Process

The ATP process was chosen early on as a promising fabrication process for the manufacturing of crown skins in the ATCAS program. One of the benefits of the ATP process is the low cost material form 938<sup>3</sup> /AS4<sup>4</sup> tow. A model was constructed for the ATP process to understand process sensitivities and how the affects of processing assumptions on cost and risk. ATP payout rate, down time, crew size, and capital investment for a variety of production rate requirements were evaluated for cost impact.

Figure 26 shows the range of crown skin costs as a function of machine pay out rates (see appendix for assumptions made in best and worst case scenarios). The pay out rate is the amount of material in pounds per hour that can be placed for a given design. In this figure, the unutilized capacity of the tow placement equipment was assumed to be used on other parts (i.e. side or keel panels), minimizing the effect of capital equipment costs. Output rates of 50 lbs/hr or more tend to isolate risks associated with the ATP process. Design details such as adding local reinforcement on skin panels affects both the total costs and cost variability due to a lower material output rate. If the design details affect the material output rate enough, the ATP process could no longer be cost effective. The effects of capital equipment costs can be important due to the relationship between material output rate and final cost. This trend may be true for other processes as well.

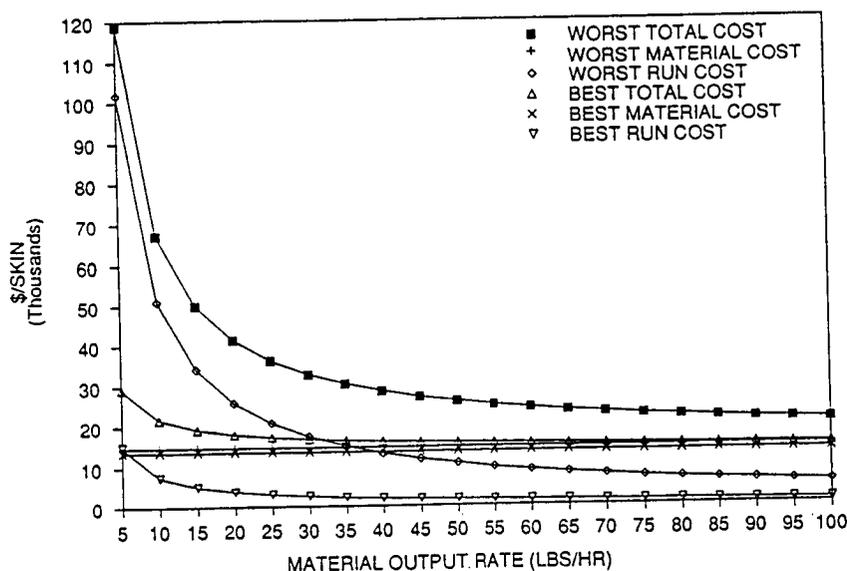


Figure 26: Composite Skin Panel Costs vs. Machine Rates

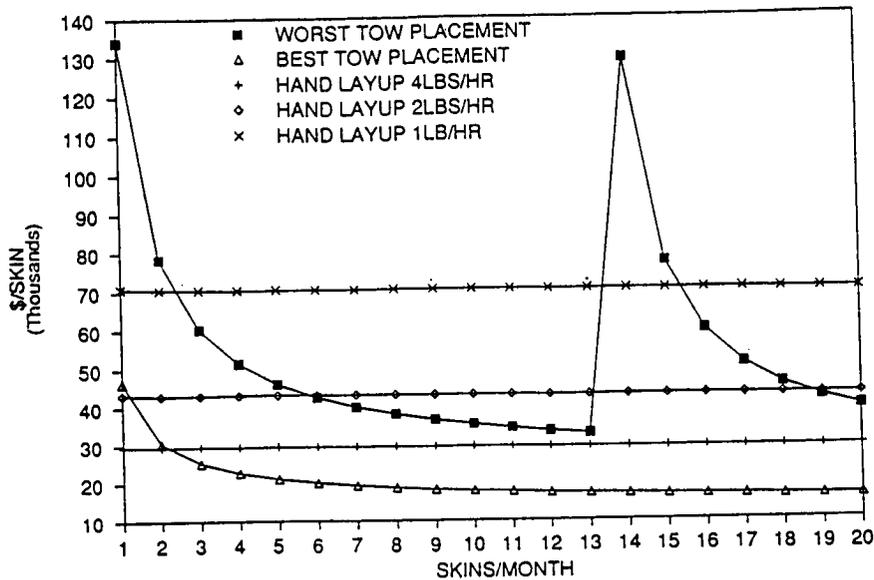
The effects of production volume on cost are shown in Figure 27. Unlike Figure 26, unused capacity of the tow placement equipment was burdened over the crown skins produced. The best and worst tow placement scenarios were evaluated and compared to a hand layup process with various output rates.

As the worst case tow placement curve approaches full utilization, additional equipment must be purchased, resulting in a spike in the curve. The curve representing the best tow placement scenario assumes a much higher material output rate and the point at which full utilization of the equipment is reached is far off the scale of crown skins/ month. Again, the relationship between design details,

3 938 is an epoxy resin system produced by ICI Fiberite

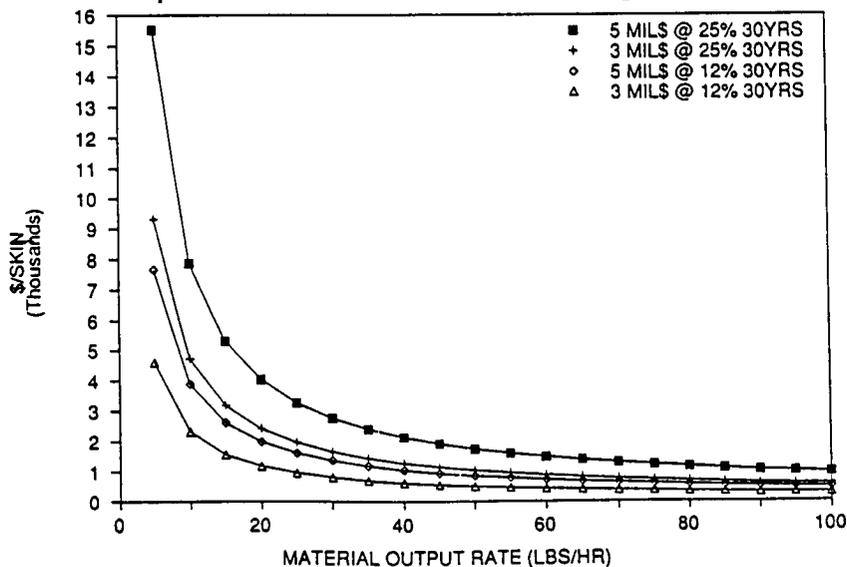
4 AS4 is a graphite fiber system produced by Hercules Inc.

material output rate, and production volume can influence the cost of implementing a given manufacturing process.



**Figure 27: Skin Panel Cost vs. Production Rates**

The effects of capital costs and rates of return burden on the production cost of crown skins are shown in Figure 28. This relationship is the dominant reason for the increased costs for low material output rates shown in Figure 26 and 27. Many factors can influence the cost of the equipment, including variable tax incentives, national interest rates, and company resources. Higher material output rates reduce the cost and risk of capital equipment related issues which dominate the costs for a low production rate or a low material output rate.



**Figure 28: Panel Costs vs. Machine Cost Rate of Return**

The evaluations shown in Figure 26-28 depict trends for ATP manufacturing risk and cost. Additional evaluations that include the effects of machine down time, machine crew sizes, and hourly pay wages must be conducted to better understand their impact to the manufacturing process.

## CONCLUSIONS AND RECOMMENDATIONS

The manufacturing technologies identified for the global crown panel configuration were demonstrated and optimized to reduce cost by 10.7 %. The demonstration panels provided warpage and panel dimensional accuracy information that is critical for determining cost and risk for fuselage assembly. Tow placed skins, resin transfer molded frames, and drape formed stringers were assembled and cured with innovative soft IML tooling and cure mandrels. The development of the innovative tooling required several manufacturing trials to minimize anomalies that would impact structural performance. Although the first manufacturing demonstrations were relatively small compared to the full size crown panel, tooling and processing parameters were selected and developed for scale-up to the 15 ft. by 31 ft. crown panels. The local optimized panel design was also evaluated with factory simulation software that further reduced cost by determining batch sizes and machine requirements. To fully realize the cost of a quadrant panel or full barrel section, additional optimization must be performed to include the keel and side quadrants. This cost optimization must include the equipment utilization for all quadrants.

The ATP technology offers significant cost advantages for fabricating large composite fuselage skins. The ATP process is capable of batch mode processing, tow placing low cost material forms, and can add / drop material on the fly. The processing rates of the ATP process can be modified depending on the required production rate with the use of multiple heads or wider material band widths. In order to maximize the cost benefits associated with the ATP automation, manual or frequent interruptive inspection tasks must be eliminated with the use of Statistical Process Control (SPC) or other automated non-interruptive inspection methods.

Use of automated composite fabrication processes must be justified by an improvement in the total part cost. The determination of which set of fabrication processes is best for a structural application is possible only after gaining some understanding of the fabrication process, structural requirements, and production rates. Given the amount of interaction between fabrication processes, design variables, and production rate ranges, computer based design models appear to be the best way to perform trades due to the many competing and reinforcing interrelationships.

Verification of crown panel processes for production readiness must be supported by additional large scale assembly demonstrations. These additional demonstrations must include evaluations of fully automated manufacturing processes to determine actual processing rates to determine final costs.

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Appendix

Assumptions for Figure 28

	<u>Best</u>	<u>Worst</u>
Cost of Capital Equipment:	\$ 3M	\$5M
Rate of Return:	12%	25%
Life:	30 yrs.	30 yrs.
Utilization:	Unused capacity used by other parts	
Production		
Hours / Month:	700	325
Skins / Month:	5	5
Material Output Rate:	Variable	Variable
Down Time:	10%	40%
Material Waste	8%	16%
Crew Size:	1	2
Hourly Rate:	\$100 / hr.	\$ 200 / hr.

Assumptions for Figure 29

Same as above except

Utilization	Unused capacity burdened over production	
Production		
Skins / Month:	5	5
Material Output Rate:	78 lbs / hr.	30 lbs /hr

Assumptions for Figure 30

Cost of Capital Equipment:	Variable
Rate of Return:	Variable
Life:	30 yrs.
Utilization:	Unused capacity used by other parts
Production	
Hours / Month:	700
Skins / Month:	5
Material Output Rate:	Variable
Down Time:	10%
Material Waste	8%
Crew Size:	1
Hourly Rate:	\$100 / hr.